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Baryonic Dark Matter and the Diffuse γ-ray Background

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ABSTRACT

We show that the baryonic gas content of the halo of our galaxy can be probed by performing a multipole expansion on the distribution of diffuse background gamma-ray emission. While the monopole moment (isotropic background) can be used to constrain the baryonic fraction of the halo gas, the quadrupole to monopole ratio is a sensitive probe of the distribution of gas in the halo, *i.e.* the degree of flattening of the gas distribution. The predicted diffuse gamma ray flux is found to be very sensitive to the adopted cosmic ray density distribution throughout the halo. If the cosmic rays are uniform, then the upper bound on the gas fraction is 16.6% regardless of the flattening of the halo gas distribution. However, this bound can be weakened by taking into account the removal of flux in and close to the galactic plane, especially for a oblate ($e < 1$) gas distribution. On the other hand, in the more realistic situation that the cosmic rays linearly trace the smoothed halo mass (and halo gas) distribution, then a stringent bound on the baryonic gas fraction in the halo η, $\eta \lesssim 3\%$, can be placed with existing data, regardless of halo flattening.

Subject headings: cosmology: dark matter — Galaxy: halo — gamma ray: theory

1 Introduction

While the existence of dark matter is now firmly established, however, despite decades of herculean efforts, its nature remains as elusive as ever. Indeed it is plausible that there is more than one type of dark matter, so that different types of dark matter dominate on different length scales. In this paper, we will focus on the smallest scale in the problem: the galactic halo scale, and address the following two questions about halo dark matter: (1) What fraction of dark matter in the halo is in the form of baryonic cold gas? and (2) How is this gas distributed in the halo? We will show how measurements of the diffuse gamma-ray background can lead to a quantitative understanding of both questions. Our study is motivated by recent suggestions that the halo dark matter may consist of dense molecular clouds (Pfenniger, Combes and Martinet 1994; Pfenniger & Combes 1994; Gerhard & Silk 1994).

Several recent papers have discussed the idea of using the diffuse gamma ray flux to constrain the fraction of halo diffuse gas (Gilmore 1994; De Paolis et al. 1994). In this paper, we use a detailed gamma-ray production function and two models of cosmic ray distribution to obtain a more accurate estimate of the diffuse gamma ray flux from baryonic gas. Furthermore, a multipole expansion of the diffuse gamma ray background is developed with the aim of exploring the possibility of detecting the flattening of halo gas distribution by measuring the multipole moments of the gamma ray background.

2 Gamma-ray Production Function

The production of gamma rays through the interaction of cosmic rays with diffuse interstellar matter and the ambient photon field is well understood (Bertsch et al. 1993). At gamma ray energies below 70 MeV, bremsstrahlung is the dominant production process. However, as shown in Fig. 1 of Bertsch et al. (1993), the contribution from bremsstrahlung is comparable to that of the nucleon interaction, and thus it is important to include this contribution. Otherwise, the gamma-ray flux will be under-estimated by roughly a factor of two at energy threshold $E_c = 70$ MeV and a factor of 1.6 at $E_c = 100$ MeV. The typical gamma-ray energy produced through inverse Compton scattering is $E_\gamma = 4E_e\epsilon_\gamma/3m_ec^2$, where E_γ is the gamma ray energy, E_e is the cosmic ray electron energy, m_e is the electron rest mass and ϵ_γ is the typical energy of diffuse photons in the galaxy. To produce gamma rays above 100 MeV, very high energy electrons are required. Since the energy threshold of gamma ray satellites COS B (Bloemen 1989) and SAS 2 (Thompson & Fichtel 1982) is above 100 MeV, it is a good approximation to neglect inverse Compton scattering as a source of diffuse high energy gamma rays.

Any spectral and spatial variations of the proton-to-electron ratio may be considered to be negligible, based on a study of life-time and secondary production (Fichtel & Kniffen 1984). Thus, the total integrated gamma ray production function can be written as

$$q_\gamma(>E_c) = \int_{E_c}^{\infty} [q_n(E) + q_e(E)] dE, \tag{1}$$

where $q_n(E)$ and $q_e(E)$ are the differential energy gamma-ray production function, per atom from interstellar material in the solar neighbour for nuclear interaction and electron bremsstrahlung respectively. We adopt the values given by Bertsch et al. (1993) for $q_n(E)$ and $q_e(E)$. The integrated gamma ray production function depends on the threshold E_c of the gamma ray detector. For E_c = 70MeV, 100MeV, 300MeV, 1GeV, the production function is $q_\gamma(>E_c) = 28.9, 22.6, 8.4, 2.1 \times 10^{-26} s^{-1}$, respectively. We will use this gamma ray production function to calculate the distribution of the diffuse gamma ray background.

3 Distribution of Diffuse γ-ray Emission

The intensity of diffuse gamma ray at galactic longitude l and latitude b is expressed in general by:

$$j(l,b) = \frac{1}{4\pi} \int c_n(\rho,l,b) q_\gamma(>E_c) n_H(\rho,l,b) d\rho \quad \gamma cm^{-2} s^{-1} sr^{-1} Gev^{-1}. \tag{2}$$

The integration is over the line-of-sight distance along l and b from the solar origin, denoted by ρ and $c_n(\rho,l,b)$ is the cosmic ray nucleon intensity relative to the local intensity, and $n_H(\rho,l,b) = [n_{HI}(\rho,l,b) + n_{HII}(\rho,l,b) + n_{H_2}(\rho,l,b)]$ is the hydrogen density.

The largest uncertainty in estimating the diffuse gamma-ray flux is the lack of any quantitative understanding of the distribution of cosmic rays in the galaxy and halo. Here we adopt the model of Bertsch et al. (1993) where the density of cosmic rays is taken to be directly proportional to the coarse-grained halo matter density. The normalized cosmic ray intensity function $c(\rho,l,b)$ is given by

$$c(\rho,l,b) = [2\pi r_0^2 \int n_m dz]_{\text{local}}^{-1} \int\int\int n_m(r',l',b') dz \times e^{(-\zeta^2/2r_0^2)} \zeta d\zeta d\psi, \tag{3}$$

where r_0 is the scale length of the coupling of matter to the cosmic rays, n_m is the total matter density, the subscript 'local' refers to the solar neighbourhood, and ζ and ψ are the relative distance and angle between point (ρ,l,b) and (r',l',b'). In using this model, any localized enhancements of the cosmic ray density through supernova explosions and hot OB stars (Gilmore 1994) is neglected, an assumption which may be justified after smoothing the diffuse background with a beam size larger than the typical angular size of active star-forming regions.

Two extreme cases for the cosmic ray distribution will be considered in this paper. The first one is for a uniform cosmic ray density, $c(\rho, l, b) = 1$, which corresponds to a large coherence length r_0. This is the model on which previous constraints on the halo gas fraction are based (Gilmore 1994). We will perform a more detailed calculation of the diffuse gamma-ray flux and discuss its dependence on the flattening of the halo gas distribution and the removal of galactic signals, effects neglected in the previous work. Note that the baryonic gas model of Pfenniger et al. (1994) assumes the halo gas to be in a disk, and that of Gerhard and Silk (1994) advocates an extremely ($\sim 1:10$) flattened halo.

To try to decide how robust our results are with respect to the cosmic ray distribution, we also consider a second case where the cosmic rays trace the smoothed matter distribution linearly (De Paolis et al. 1994), i.e., $c(\rho, l, b) = n_H(\rho, l, b)/n_H(\rho = 0)$. This is the limiting case where the coherence length of the cosmic ray distribution is negligibly small compared with the size of the galaxy. These two models bracket the theoretical predictions expected for any realistic cosmic ray intensity function. According to Bertsch et al. (1993), the coherence length is required to be $r_0 \sim 2$kpc in order to fit the gamma ray emission in the galactic plane. The coupling scale is much larger than the linear size adopted for the cold molecular hydrogen clouds in the model of Gerhard & Silk (1994), but much smaller than the size of the galaxy. Thus, the case where the cosmic rays linearly trace the smoothed matter distribution is probably closer to reality. As we will show later, this leads to a more stringent constraint on the baryonic fraction of dark halo.

3.1 Diffuse Hydrogen Gas in the Halo

The halo distribution of diffuse hydrogen gas is modeled to be a spheroid with flattening e and core radius $r_c = 3.5$ kpc,

$$n_m(R, z) = n_0(r_c^2 + R^2 + \frac{z^2}{e^2})^{-1}. \tag{4}$$

The mass of halo hydrogen gas within radius $r (r \gg r_c)$ of the galactic center is $M_H = 4\pi m_H n_0 r \Gamma(e)$, here m_H is the mass of a hydrogen atom and

$$\Gamma(e) = \int_0^1 \frac{dx}{(1-x^2) + \frac{x^2}{e^2}} = \begin{cases} \frac{e}{\sqrt{1-e^2}} \tan^{-1}\sqrt{1-e^2}/e & \text{if } e < 1, \\ 1 & \text{if } e = 1, \\ \frac{e}{\sqrt{e^2-1}} \tanh^{-1}\sqrt{e^2-1}/e & \text{otherwise.} \end{cases} \tag{5}$$

The total mass M_D of a dark halo truncated at radius R_m is known through the rotation curve, $M_D = v_c^2 R_{max}/G$, where v_c is the circular velocity of a halo tracer. If the rotation curve continues to be flat up to $R_m \approx 50kpc$, then the total dark matter mass is $M_D = 10^{12} M_{cdot}$ for $v_c = 300$km/s. The baryonic mass fraction of the dark halo is then $\eta = M_H/M_D = n_0 4\pi\Gamma(e)G/v_c^2$.

Parametrized in terms of η and e, the halo gas distribution is given by

$$n_m(R,z) = \eta \frac{v_c^2}{4\pi\Gamma(e)G}(r_c^2 + R^2 + \frac{z^2}{e^2})^{-1}. \quad (6)$$

The expected diffuse gamma-ray flux is estimated for two limiting cases of the cosmic ray distribution:

(i) The density of cosmic ray is uniform throughout the halo.

The diffuse gamma-ray distribution from halo clouds is

$$j(l,b) = \frac{1}{4\pi}\eta \frac{v_c^2}{4\pi\Gamma eG} q_{nm}(> E_c) \int_0^{R_{max}} \frac{1}{(r_c^2 + R^2 + z^2/e^2)} d\rho, \quad (7)$$

Inserting numerical values, the diffuse flux of gamma-rays with energy higher than 100 MeV is $j(l,b) = 7.24 \times 10^{-5} \eta f(l,b) \ \ \gamma cm^{-2} sr^{-1} s^{-1}$. where the angular distribution $f(l,b)$ is given by

$$f(l,b) = \frac{1}{\Gamma(e)} \int_0^1 \frac{1}{A + Bx + Cx^2} dx, \quad (8)$$

here

$$A = \frac{R_0^2 + r_c^2}{R_m^2}, \quad B = -2\frac{R_0}{R_m}\cos(l)\cos(b), \quad C = \cos^2(b) + \sin^2(b)/e^2. \quad (9)$$

It is useful to expand the background gamma-ray radiation into multipole moments, i.e.

$$f(l,b) = \sum_l \sum_{m=-l}^{l} a_{lm} Y_{lm}(l,b), \quad (10)$$

where $Y_{lm}(l,b)$ is the spherical harmonics. The monopole term,

$$a_0 = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} \cos(b) db dl f(l,b), \quad (11)$$

is the uniform component of the sky distribution, which we may use to constrain the baryonic fraction of the halo. The dipole moment $D(l,b)$ has three components,

$$D(l,b) = D_1 \sin(b) + D_2 \cos(b)\sin(l) + D_3 \sin(b)\sin(l), \quad (12)$$

where D_i, $i = 1,2,3$ are the dipole coefficients. The dipole moment of the gamma ray sky is non-vanishing even if the gas distribution is uniform because we are located at a distance of 8.5kpc away from the galactic center. The quadrupole moment $Q(l,b)$ is

$$Q(l,b) = Q_1 \frac{3\sin^2 b - 1}{2} + Q_2 \sin 2b \cos l + Q_3 \sin 2b \sin l + Q_4 \cos^2 b \cos 2l + Q_5 \cos^2 b \sin 2l, \quad (13)$$

where $Q_i, i = 1, ..., 5$ are quadrupole coefficients.

Due to the symmetry of the model hydrogen distribution, the non-vanishing multipole moments are a_0, D_3 and Q_1, so the distribution function $f(l, b)$ is given by,

$$f(l,b) = a_0 + D\cos(b)\cos(l) + Q\frac{3\sin^2(b) - 1}{2}, \tag{14}$$

The uniform diffuse gamma ray background $j_0(\gamma)$ is found to be $j_0(\gamma) = 7.24 \times 10^{-5}\eta a_0$. The isotropic gamma-ray emission determined from SAS 2 is $1.2 \times 10^{-5}\gamma(E > 100Mev)$ $\mathrm{cm^{-2}s^{-1}sr^{-1}}$. Provide that all of this background is produced by the hydrogen gas in the halo, the upper limit on the halo baryonic fraction is given by $\eta \lesssim 0.166/a_0(e)$. As we show in the left panels of Fig.1, a_0 is not a sensitive function of the flattening parameter e, which reflects the fact that the gamma ray flux only traces the total column density along the line of sight. In the flattening range $e = 0.3 - 1.4$, the monopole term deviates very little from unity. This translates to a limit on the baryonic fraction of halo as $\eta \lesssim 16.6\%$, in agreement with Gilmore (1994). The ratios of dipole moment D and quadrupole moment Q to the monopole term are shown in the left panels of Fig.1 as a function of e. As expected, the dipole moment is insensitive to the change of e since it reflects only the fact that our location is off-center. On the contrary, the quadrupole moment changes rapidly as the distribution of gas deviates from sphericity.

In practice, to estimate all of the multipole terms, the flux from the galactic plane has to be removed very carefully. Systematic galactic cuts need to be performed which will however inevitably remove gamma ray flux produced by halo gas. To see how this affects the predictions of various multipole moments, in the right panels of Fig. 1, we plot the monopole, dipole/monopole, quadrupole/monopole after a 30 degree cut, as a function of flattening e. The reduction in predicted gamma-ray flux is considerable, especially for $e < 1$. For example, after the 30 degree cut, the isotropic gamma ray flux for $e = 0.3$ is $1.4\eta \times 10^{-5}\gamma cm^{-2}s^{-1}sr^{-1}$, which is consistent with the SAS 2 observation even for a gas-dominated halo. No upper bound on halo baryonic gas fraction can therefore be achieved through gamma ray measurements.

On the contrary, the quadrupole to monopole ratio is enhanced after performing the galactic cut. This makes it more appealing to use the quadrupole to monopole ratio to first constrain the flattening e of the halo gas distribution . Only after the parameter e is better constrained could one hope to use the isotropic background at high galactic latitude to constrain the baryonic gas fraction.

(ii) Model 2: cosmic rays linearly trace the smoothed matter distribution.

The interrelation of cosmic rays with the matter distribution is an unsolved issue which still lacks clear understanding. However, it is evident that, after smoothing the matter density over some length scale, there is a correlation with cosmic ray density. One of the first such observations, by Puget et al. (1976), found that the cosmic ray intensity has to

be 1.9 to 4.8 times the local (solar system) value in a region 5 kpc away from the galactic center. A more detailed discussion of this issue can be found in Bertsch et al. (1993). If cosmic rays linearly trace the mass, the diffuse gamma-ray distribution from halo clouds is

$$j(l,b) = \frac{1}{4\pi} n_0 q_{nm}(> E_c) \int_0^{R_m} \frac{R_0^2 + r_c^2}{(r_c^2 + R^2 + z^2/e^2)^2} d\rho, \tag{15}$$

Inserting the numerical values, the diffuse flux of gamma-rays with energy higher than 100 MeV is $j(l,b) = 7.24 \times 10^{-5} \eta g(l,b) \ \ \gamma cm^{-2} sr^{-1} s^{-1}$, where the angular distribution $g(l,b)$ is given by

$$g(l,b) = \frac{r_c^2 + R_0^2}{R_m^2} \int_0^1 \frac{1}{(A + Bx + cx^2)^2} dx, \tag{16}$$

and A, B, C are given in Eq.(9). Similar to what has been done in model (1), a multipole expansion of this sky distribution is performed up to quadrupole terms. The monopole term is found to be enhanced over that in model (1) by a factor of 20 over the range of flattening e we consider. In this model, the upper bound on the halo density is rather stringent: $\eta \lesssim 1\%$. Less than one percent of the dark matter could be in the form of diffuse gas which is capable of producing gamma ray. Although the galactic cut will also reduce the estimated monopole flux, the upper limit still remains strong: $\eta \lesssim 3\%$.

Another clear feature of the diffuse background gamma ray flux is the large dipole moment which points toward the galactic center if cosmic rays indeed trace the mass distribution. The dipole drops dramatically after a 30 degree galactic cut since it lies mainly in the galactic plane. The quadrupole term remains large but flips sign to point towards the galactic poles.

In summary, we have shown that much can be learnt about baryonic gas in the halo through a multipole expansion of the diffuse background gamma-ray intensity. While the monopole moment (isotropic background) can be used to constrain the baryonic fraction of the halo gas, the quadrupole to monopole ratio is a sensitive probe of the distribution of gas in the halo, i.e., the flattening parameter of the gas distribution. We also have found that our predictions are very sensitive to the cosmic ray density distribution throughout the halo. If the cosmic rays are uniform, then an upper bound on the gas fraction is found to be 16.6% regardless of the flattening of the halo gas distribution. However, this bound can be evaded by taking into account the removal of flux in and close to the galactic plane, especially for a oblate ($e < 1$) gas distribution. On the other hand, if the cosmic rays linearly trace the smoothed mass distribution, then a rather stringent bound on the baryonic gas fraction of the halo η, $\eta \lesssim 3\%$ is placed through current data.

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Figure Caption

Fig.1: The monopole, dipole and quadrupole moment of the diffuse gamma ray background for a spheroidal halo gas distribution as a function of the axis ratio e. The isotropic background flux is equal to the monopole term a_0 times a numerical constant, $7.24 \times 10^{-5}\eta$ γ cm^{-2} s^{-1} sr^{-1}, where η is the gas fraction of the halo. The left panels are for full sky coverage. The right panels are for a 30 degree galactic cut.